

Temporal integration property of stereopsis after higher-order aberration correction

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Abstract: Based on a binocular adaptive optics visual simulator, we investigated the effect of higher-order aberration correction on the temporal integration property of stereopsis. Stereo threshold for line stimuli, viewed in 550nm monochromatic light, was measured as a function of exposure duration, with higher-order aberrations uncorrected, binocularly corrected or monocularly corrected. Under all optical conditions, stereo threshold decreased with increasing exposure duration until a steady-state threshold was reached. The critical duration was determined by a quadratic summation model and the high goodness of fit suggested this model was reasonable. For normal subjects, the slope for stereo threshold versus exposure duration was about -0.5 on logarithmic coordinates, and the critical duration was about 200 ms. Both the slope and the critical duration were independent of the optical condition of the eye, showing no significant effect of higher-order aberration correction on the temporal integration property of stereopsis.

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OCIS codes: (330.0330) Vision, color, and visual optics; (330.4595) Optical effects on vision; (330.1400) Vision - binocular and stereopsis.

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1. Introduction

Living in a three-dimensional world, it is crucial for us to know about the depth information of space objects. However, the retinal image of human eye is two-dimensional, from which depth information cannot be directly obtained. There are various cues that the human visual system can employ to recover depth information, such as occlusion, perspective, motion parallax and stereopsis. Among these cues to depth, stereopsis has been proved to be the most accurate one. Based on the detection of binocular disparity that originates from the slightly different point of view of the two horizontally separate eyes, we can discriminate a depth difference smaller than the size of a photoreceptor [1]. The functional importance of stereopsis has been demonstrated for situations that require manual skills [2,3]. In clinical practice, stereopsis is routinely tested as a screening for visual disorders.

Exposure duration plays an important role in stereopsis. Ogle and Weil [4] measured stereo thresholds for line targets (local stereopsis) at a range of durations from 5 ms to 1000 ms. They discovered a continuous decrease in stereo threshold as exposure duration was increased. This relationship was approximately linear on logarithmic coordinates, with a slope of about -0.3 . Pianta and Gillam [5] found a slope of about -0.3 to -0.4 for local stimuli of two square panels. A similar phenomenon was observed for random-dot stereograms (global stereopsis) in both human [6] and monkey subjects [7], except that the slope was -1 rather than -0.3 . This temporal integration property of disparity information seems analogous to other detection tasks, such as luminance, that follow Bloch's law [8]. Recently, it was demonstrated for both line targets and random-dot stereograms that the temporal integration of stereopsis was limited to a critical duration, beyond which the threshold was almost constant [9,10]. The critical duration actually estimates the time essential for complete integration of disparity information. So it is another important parameter indicating the efficiency of stereo mechanisms besides the slope. To account for the improvement of stereoacuity with time, several investigations proposed a channel hypothesis in which the sequential employment of finer disparity-sensitive channels operate at higher spatial frequencies [11,12]. Specifically, channels activated by low spatial frequencies are sensitive at short durations and channels activated by high spatial frequencies are sensitive at long durations.

Efforts have been made with respect to the impact of other factors affecting the temporal integration property of stereopsis. In their research on the role of involuntary eye movements in stereopsis, Shortess and Krauskopf [13] found that there was no significant difference in

the rate of decrease of stereo threshold with increasing exposure duration between normal and stabilized viewing conditions. Harwerth et al. [9] investigated the dependence of critical duration on stimulus parameters such as contrast and spatial frequency. The results suggested that the critical duration was about 100ms for both local and global stereoscopic stimuli, independent of stimulus contrast and spatial frequency, although the stereo thresholds differed across conditions. Hess and Wilcox [14] further confirmed with different stimulus configurations that the stereo dynamics did not vary with stimulus spatial frequency. However, Lee et al. [10] showed a clear dependence of critical durations on the spatial frequency of the stimuli. The critical duration was about 250 ms for spatial frequencies of 0.23 and 0.94 cycles per degree (cpd), and increased to about 750 ms for the higher spatial frequency of 3.75 cpd.

The optical quality of the eye might influence the temporal properties of stereopsis. Higher-order aberration (HOA) correction has been shown to improve contrast sensitivity, especially for high spatial frequencies [15]. That is to say, higher spatial frequency contents beyond detection of normal eyes can be perceived after AO correction. According to the channel hypothesis, these higher spatial frequency contents after AO correction might take longer time for the visual cortex to process and lead to better steady-state stereoacuity.

In an earlier paper [16], employing a binocular adaptive optics visual simulator (BAOVS), we demonstrated that dynamic HOA correction using adaptive optics had a significant effect on stereopsis and the stereo benefit was related to the exposure duration. However, the data were not sufficient to infer whether the curve for stereo threshold versus exposure duration would change after HOA correction. In this article, this issue is further investigated. HOA correction is performed either in both eyes or in one eye only so that the effect of interocular differences in aberrations can be evaluated.

2. Methods

2.1 Apparatus

The BAOVS used in this study was described in detail elsewhere [16]. The schematic diagram of the BAOVS is shown in Fig. 1. In brief, it comprises two identical monocular channels capable of sensing and manipulating binocular aberrations and simultaneous visual function testing. Each monocular channel contains a Hartmann-Shack wavefront sensor with 97 lenslets, a piezoelectric deformable mirror with 37 actuators and an organic light emitting diode (OLED; EMA-100110, eMagin Corporation, Washington, USA) micro-display projecting dichoptic visual stimuli. The wavefront sensor and the deformable mirror are laboratory prototypes. Aberrations are controlled in real-time over a 6mm pupil. AO correction is suspended during eye blinks or other situations where the lenslets of the wavefront sensor are not fully filled with light. The visual stimuli are generated and controlled with computer programs developed by Matlab 6.5 (Mathworks, Natick, Massachusetts) and Psychtoolbox extensions. The chromatic focus shift between wavefront sensing light (907 nm) and visual stimulus (550 nm) is eliminated by subjective best-focus search of the observer. For this purpose, the micro-displays are mounted on a translational stage which is driven by a stepping motor. A trapezoidal reflecting prism is used for inter-pupillary distance adjustment between 55 and 70 mm. Head movements are stabilized by a forehead and chin rest.

In this research, defocus and astigmatism are corrected by trial lenses. Therefore, AO is mainly responsible for correcting HOAs. Vertical and horizontal tilts were retained to avoid changes in the relative position of retinal images.

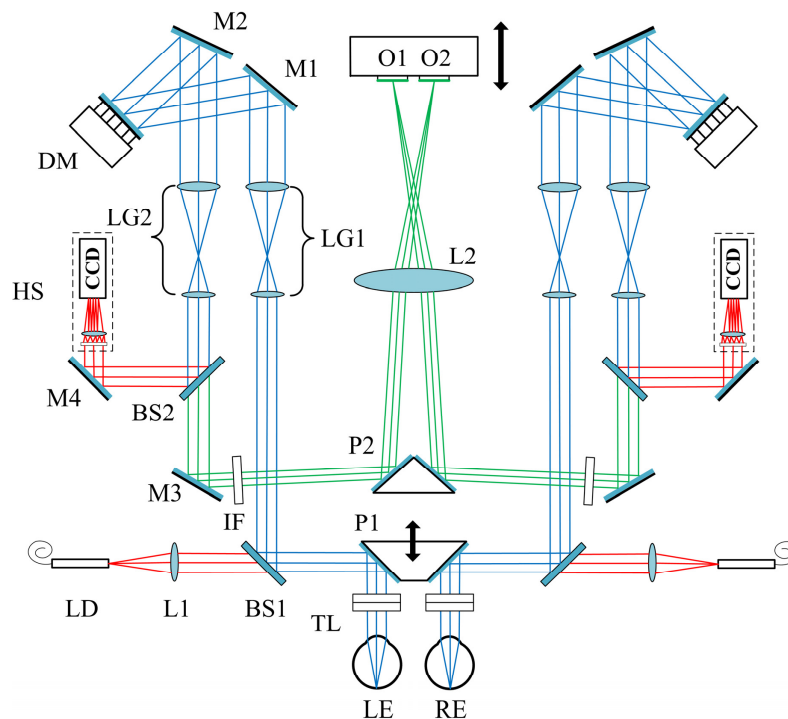


Fig. 1. Schematic diagram of the BAOVS used in this study. LD, laser diode; BS, beam splitter; HS, Hartmann-Shack wavefront sensor; DM, deformable mirror; LG, lens group; TL, trial lens; IF, interference filter; L, lens; M, mirror; P, prism; O, OLED; LE, left eye; RE, right eye.

2.2 Subjects

Four experienced subjects (age: 31 ± 7 years) were recruited in this study. They had no previous history of ocular trauma or visual disorders and had normal corrected vision. Table 1 shows basic information on the optical quality of both eyes of the subjects. The refraction was performed with a wavefront analyzer (KR-1W, Topcon Corporation, Tokyo, Japan). Each eye of the subject was corrected with trial lenses to a decimal acuity of 1.5. Natural HOAs and residual HOAs (upon AO correction) were measured over a 6mm pupil with the BAOVS and the data are given in root mean square (RMS). Pupil was dilated and accommodation was paralysed through administering 1% cyclopentolate solution. All procedures were in accordance with the tenets of the Declaration of Helsinki. Before their participation, signed informed consent was obtained from the subjects.

Table 1. Optical quality of both eyes in the four subjects

| Subject | Refractive error | | | | | | HOA(μm) | | | |
|---------|------------------|-------|--------|-------|-------|--------|----------------------|----------|---------|----------|
| | OD | | | OS | | | OD | | OS | |
| | S(D) | C(D) | A(deg) | S(D) | C(D) | A(deg) | Natural | Residual | Natural | Residual |
| 1 | -1.75 | -0.25 | 97 | -1.50 | -0.25 | 127 | 0.38 | 0.09 | 0.43 | 0.08 |
| 2 | -0.75 | -0.75 | 90 | -0.75 | -0.25 | 101 | 0.25 | 0.06 | 0.24 | 0.05 |
| 3 | -2.00 | -0.50 | 107 | -1.75 | -0.75 | 86 | 0.31 | 0.08 | 0.36 | 0.07 |
| 4 | -1.00 | -0.25 | 178 | -1.25 | -0.50 | 1 | 0.24 | 0.04 | 0.30 | 0.06 |

2.3 Procedures

Contrast sensitivity function was measured for each eye of the four subjects with and without HOA correction to evaluate the effectiveness of our optical manipulation. The stimuli were sine wave luminance gratings in the form of

$$L(x, y) = L_0(1 + c \sin(2\pi f(y \sin \theta + x \cos \theta) + \varphi)) \quad (1)$$

where $L(x, y)$ is the luminance of the pixel (x, y) , L_0 is the background luminance corresponding to about 8 cd/m², c is the contrast, f is the spatial frequency. We test 2, 4, 8, 16 and 24 cpd in this study. θ is the orientation and set to zero so that vertical gratings are presented, and φ is a random phase from 0 to 2π so that the horizontal position of the gratings differ from trial to trial. The visual angle of the gratings was 1.25°. In each trial, two brief presentations (100 ms) were shown sequentially and gratings were randomly assigned to one of them. The subject was asked to decide which one contained the gratings. The contrast threshold was obtained through the three-down-one-up staircase procedure [17]. Data from eight staircases of 50 trials each were combined to determine the contrast threshold for each spatial frequency as the average of the last five reversals.

Local stereopsis was tested in this study using line stimuli (Fig. 2). The stimuli were two vertical dark lines on a bright background. The retinal illumination was 8 cd/m². The two lines had identical dimensions of 2' × 25' and were 4' vertically apart. The comparison line had zero disparity and lay within the plane of the OLED screen. The test line had variable disparity in either crossed or uncrossed direction, and thus appeared to be in front of or behind the screen when viewed stereoscopically. During the experiment, the subject was asked to fixate on the comparison line and decide whether the test line was relatively farther or nearer. The stereo threshold was measured using the method of constant stimuli. The disparities tested were 20, 80, 140 and 200 arc sec in both crossed and uncrossed directions. The experiment process was arranged in five sessions. Each session contained 80 trials presenting the eight disparities equally in random order. A central cross sign was presented between trials to maintain fixation. It took about half an hour for one subject to finish all sessions for one threshold measurement. Breaks were optional between sessions to avoid visual fatigue. The psychometric data from all sessions were combined and the proportion of “far” responses was calculated for each disparity. Then these data were subjected to a least-square fit of the logistic function, and its semi-interquartile range was the stereo threshold. The stereo threshold measures were repeated for different combinations of six exposure durations (50, 100, 300, 500, 800 and 1100 ms) and three optical conditions of the eyes as follows: (i) baseline correction of defocus and astigmatism for both eyes; (ii) monocular (better eye) HOA correction beyond the baseline correction; (iii) binocular HOA correction beyond the baseline correction. Here, better eye means the eye with better contrast sensitivity measured with the aforementioned procedures.

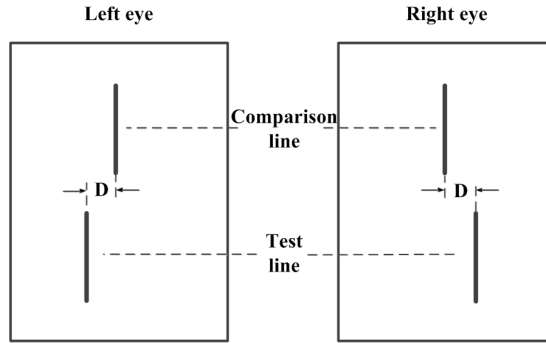


Fig. 2. Line stereograms used in this study. The comparison line and the test line had identical dimensions. Disparity was generated by horizontal displacement of the test line in opposite directions by the same distance D between eyes.

The stereo thresholds were plotted as a function of exposure duration on a log-log scale and the data points were fitted to a line to derive the slope factor of temporal integration for binocular disparity. The critical duration was obtained through a quadratic summation model [9] defined by

$$th = h_0 (d^{-2} + d_0^{-2})^{0.5} \quad (2)$$

where th is the stereo threshold at the exposure duration d , h_0 is a constant determining the vertical position of the function and d_0 is the critical duration. When d is much larger than d_0 , d^{-2} becomes vanishingly small compared to d_0^{-2} and the threshold th approaches a steady-state level of h_0/d_0 . All curves were fitted using the least-square method.

3. Results

3.1. Contrast sensitivity function

Figure 3 shows the average results for monocular contrast sensitivity function over the four subjects. Inter-subject differences were small and this pattern of results was typical of all subjects. HOA correction improved contrast sensitivity at all spatial frequencies. For the left eye, this improvement was by a factor of 1.20, 1.28, 1.48, 1.76 and 1.51 at 2, 4, 8, 16 and 24 cpd, respectively. Corresponding values for the right eye were 1.26, 1.53, 1.47, 1.68 and 1.62, respectively. It could be seen that the visual benefit was generally larger at higher spatial frequencies. The largest benefit occurred for the left eye of Subject 4 at the spatial frequency of 16 cpd, although Subject 1 had the largest amount of HOAs corrected. We submitted these data to a paired t-test and the results revealed that the contrast sensitivity improvement was statistically significant for all spatial frequencies ($p < 0.05$), indicating that our optical manipulation was effective.

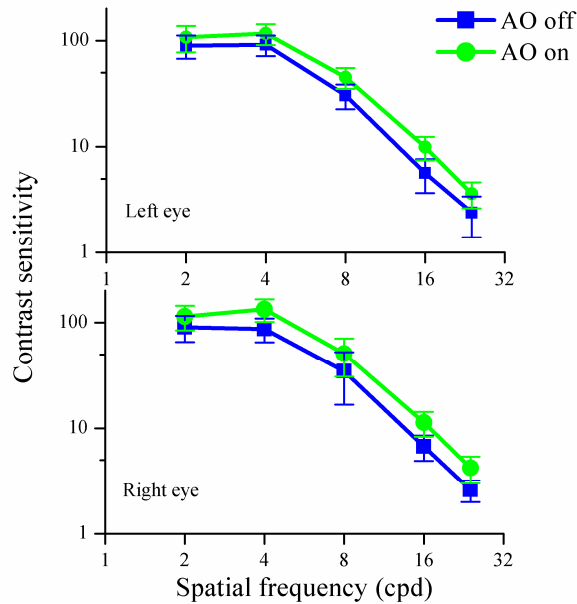


Fig. 3. Monocular contrast sensitivity function averaged across the four subjects. The blue squares represent contrast sensitivity measured with baseline correction of defocus and astigmatism (AO off). The green circles represent contrast sensitivity measured with AO correction of HOAs (AO on). Error bars indicate standard deviations.

3.2. Stereo threshold as a function of exposure duration

Figure 4 shows the log-log plot of the stereo threshold as a function of exposure duration for different optical conditions in the four subjects. Stereo threshold decreased with increasing exposure duration in all cases, showing a clear property of temporal integration of disparity information. Binocular HOA correction brought a marked decrease of stereo threshold for all subjects. However, monocular HOA correction could lead to either lower (for Subject 1, 2, and 3) or higher thresholds (for Subject 4). These were consistent with our previous results [16]. The slopes of the fitted lines under different optical conditions are given in Table 2. The slopes were about -0.5 for Subject 1, 2, and 3. Subject 4 behaved poorly at short durations, with no depth perception at 50ms even for the largest disparity tested (± 200 arc sec). However, he had comparable stereo performances to the other subjects at longer durations. Consequently, the slope for Subject 4 was a little larger (absolute value), in the range of -0.6 to -0.8 . On average across all subjects, the slope was about -0.5 . This value was slightly different from previous results which revealed slopes of about -0.3 or -0.4 for local stereopsis [4,5]. The slope data were referred to a two-way analysis of variance (ANOVA) with factors being subject and optical condition. The results indicated no significant effect of optical condition on the slope ($F_{(3,2)} = 0.924$, $p = 0.447$).

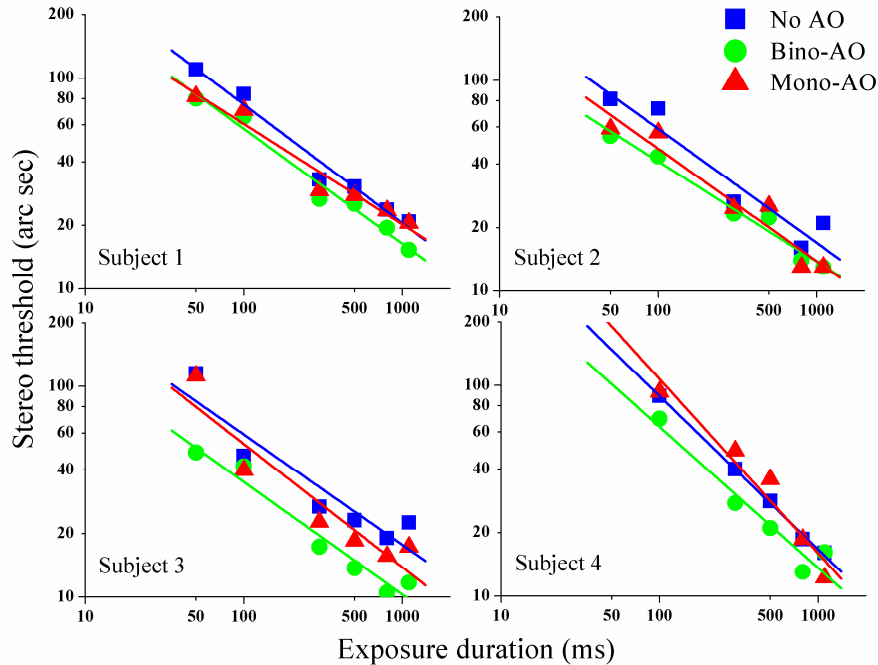


Fig. 4. Linear fit of stereo threshold versus exposure duration data on a log-log scale. The blue squares represent stereoacuity with baseline correction of defocus and astigmatism (No AO). The green circles and red triangles represent stereoacuity with binocular HOA correction (Bino-AO) and monocular HOA correction (Mono-AO), respectively.

Table 2. The slope of the fitted line for stereo threshold versus exposure duration

| Subject | Slope | | |
|---------|-------|---------|---------|
| | No AO | Bino-AO | Mono-AO |
| 1 | -0.56 | -0.54 | -0.47 |
| 2 | -0.54 | -0.47 | -0.53 |
| 3 | -0.52 | -0.53 | -0.58 |
| 4 | -0.72 | -0.67 | -0.82 |

The data for stereo threshold versus exposure duration were also fitted to the quadratic summation model predicting complete temporal integration of disparity information, as described by Eq. (2). Figure 5 depicts the fitted curve under different optical conditions for the four subjects. In all subjects, stereo threshold decreased with increasing exposure duration up to a certain duration and then leveled off. Table 3 lists the best-fit parameters of this model and the steady-state thresholds derived accordingly. From the high goodness of fit ($R^2 > 0.85$), our data fitted well with this model. Inter-individual differences were small between Subject 1, 2, and 3, for whom the critical duration was commonly in the range of 150 to 350 ms, with a mean value of about 200 ms. This was larger than the results of Harwerth et al. who observed a critical duration of about 100 ms for both local and global stereopsis [9]. For Subject 4, despite the critical duration was much longer (about 500ms), there was little difference across optical conditions. For all subjects the steady-state threshold varied with optical condition, but the critical duration did not. Further statistical analysis through a two-

way ANOVA with factors subject and optical condition supported this finding, showing no significant effect of optical condition on critical duration ($F_{(3,2)} = 0.876, p = 0.464$).

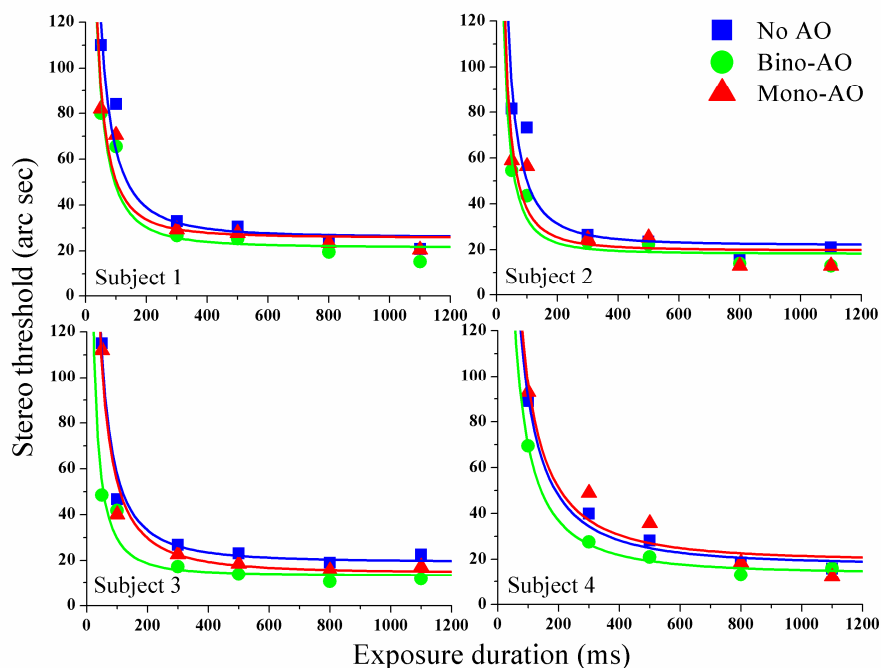


Fig. 5. Stereo threshold versus exposure duration under different optical conditions for the 4 subjects on linear scales. The blue squares represent stereoacuity with basic correction of defocus and astigmatism. The green circles and red triangles represent stereoacuity with binocular and better eye correction, respectively.

Table 3. Best-fit parameters of the quadratic summation model

| Subject | Condition | h_0 | d_0 | $th_0 = h_0/d_0$ |
|---------|-----------|-------|-------|------------------|
| 1 | No AO | 5833 | 225.4 | 25.9 |
| | Bino-AO | 4280 | 200 | 21.4 |
| | Mono-AO | 4359 | 169.8 | 25.7 |
| 2 | No AO | 4479 | 204.4 | 21.9 |
| | Bino-AO | 2815 | 155.1 | 18.1 |
| | Mono-AO | 3230 | 164.7 | 19.6 |
| 3 | No AO | 5399 | 269.2 | 20.1 |
| | Bino-AO | 2646 | 213.8 | 12.4 |
| | Mono-AO | 5200 | 340.8 | 15.3 |
| 4 | No AO | 8913 | 510.4 | 17.5 |
| | Bino-AO | 6852 | 502.5 | 13.6 |
| | Mono-AO | 9517 | 494.2 | 19.3 |

4. Discussion

This study concentrated on the effects of HOA correction on the temporal integration property of stereopsis. The optical correction was performed either binocularly or monocularly in the better eye. The temporal integration property of stereopsis was characterized by two parameters, the slope and the critical duration. The principal finding was the independence of these parameters on the optical condition of the eye, suggesting no systematic effect of HOA correction on the temporal integration property of stereopsis. Optical correction improves the eye's modulation transfer function (MTF) which measures the ratio of object contrast delivered to retinal image at each spatial frequency. For the broadband line stimuli used in this study, HOA correction could improve retinal contrast and enhance visual detectability of higher spatial frequency components. In the work of Harwerth [9], they changed stimulus contrast and spatial frequency to see the effect on critical duration of stereopsis. Both ways lead to the same results of changing retinal contrast and spatial frequency, and the critical duration was observed to be independent of these factors in both papers. In this sense, our results could be reconciled with those obtained by Harwerth et al. By inference, the temporal integration property of stereopsis is inherent to the neural mechanisms responsible for disparity information integration and independent of the anterior parts on the visual pathway.

A slope of -0.3 was found by Ogle and Weil [4] in their study of temporal integration of stereopsis for line stimuli. Pianta and Gillam [5] found similar values of about -0.3 to -0.4 for local stereopsis, although the stimuli features were square panels rather than lines. On average across subjects, the slope obtained in this study was about -0.5 , which was slightly different from previous results. This might be due to the differences in experimental methods and conditions. It should be noted that our results were not perfectly modeled by a line. The linear model for stereo threshold versus exposure duration predicts partial summation of disparity information over time, without a constant threshold for long durations. However, our results obviously demonstrated complete summation (Fig. 5). The slope was used as a parameter of temporal integration of stereopsis because it could indicate the mean rate of decrease of stereo threshold with exposure duration and reflect differences between optical conditions. In addition, a slope of -0.5 meant that the stereo threshold was inversely proportional to the square-root of exposure duration. This relationship was also observed when Legge and Gu [18] measured stereo threshold as a function of stimulus contrast for a given exposure duration. These results show collectively that the output of the disparity integrator might exhibit an inverse square-root dependence on the product of contrast and time. Another thing noteworthy is that the slope for local stereopsis generally has a smaller magnitude than that for global stereopsis (about -1), which suggested a smaller rate of decrease and consequently less dependence of stereo performance on exposure duration.

Although our results suggest that the temporal integration property of stereopsis is unaffected by HOA correction, it does not necessarily mean HOAs can be arbitrarily altered in clinical applications such as LASIK. Binocular HOA correction provides a reliable benefit of stereo performance across the whole continuum of exposure duration. However, monocular HOA correction, which induces interocular difference in aberrations, brings inconsistent results—either a slight improvement or degradation depending on the specific individual. Therefore, it is important to evaluate the binocular aspects of vision in clinical applications where interocular differences could appear. In this respect, the influence of two clinical approaches to correcting presbyopia, monovision and small aperture inlay, has been studied on binocular visual acuity [19,20] and stereoacuity [21]. BAOVS is a powerful tool for visual simulation under controlled optical condition of the eye and can help to predict the visual outcomes in wavefront-guided refractive surgery such as LASIK. Vision research based on BAOVS explores the relationship between eye optics and visual function, in an effort to seek the optimum aberration correction to achieve maximum visual performance. For example, Sabesan et al. [22] recently showed that binocular HOA correction led to a significant improvement in binocular visual acuity and contrast sensitivity. However, the binocular summation for contrast sensitivity at high spatial frequencies was decreased by such

correction. Schwarz et al. [23] later found a similar effect of spherical aberration correction on binocular visual acuity and summation in both monochromatic and polychromatic light. Other researches involved the optical effect on stereopsis [16,24] and depth of focus [25]. On the whole, relevant results are limited so far and further efforts are expected in the future. Particularly, accommodation is another important visual function yet to be explored on a binocular basis.

In conclusion, based on a binocular AO visual simulator, we investigated the effects of HOA correction on the temporal integration property of stereopsis. The stereo threshold decreased with increasing exposure duration until a steady-state threshold was reached. For normal subjects, the slope for stereo threshold versus exposure duration was about -0.5 on logarithmic coordinates, and the critical duration was on the order of 200 ms. Both the slope and the critical duration were independent of the optical condition of the eye, showing no systematic effect of HOA correction on the temporal integration property of stereopsis.

Acknowledgments

This research was supported by the National Natural Science Foundation of China (Grant Nos. 61205202 and 61378064) and the National High Technology Research and Development Program of China (Grant No. 2015AA020510). The authors would like to thank Professor Wenhan Jiang and the anonymous reviewers for their critical comments and thoughtful suggestions. We thank our subjects for their supports in this work.